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MEASUREMENTS OF THE TOTAL ELECTRON CONTENT AND THE EQUIVALENT SLAB THICKNESS OF THE MID-LATITUDE IONOSPHERE

By

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ABSTRACT

The total electron content N_T and the equivalent slab thickness τ of the mid-latitude ionosphere are determined from differential Doppler measurements on the radio transmissions from the Transit 4A satellite and the ionosonde data near Washington, D. C. and Ottawa. The trends of diurnal, seasonal, and sunspot cycle variations of N_T and τ at midday are described. It is found that in 1962 both N_T and τ were considerably decreased in magnitude as compared to the corresponding values near the peak of the sunspot cycle. The inferred mean electron-ion temperature is found to be generally in excess of the neutral gas temperature. The ratio T_e/T_g in the daytime is estimated to be 1.8 in summer and about 1.1 to 1.2 in winter, which may reflect corresponding changes in the ratio Q/N_e^2, where Q is the heat input to the electrons and N_e is the electron density. The relationship between τ and K_p appears to be rather ambiguous in contrast with the positive correlation between the neutral gas temperature and K_p.

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FIGURE CAPTIONS

Figure 1. Some sample plots of N_T against geographic latitude of the sub-ionospheric point of Transit 4A satellite in 1962. T_o represents the proximal point of satellite passage.

Figure 2. The total electron content N_T of the ionosphere deduced from Transit 4A differential Doppler measurements at (a) 40^oN and (b) 45^oN geographic latitudes.

Figure 3. Mean diurnal variation of N_T at 40^oN and 45^oN (geographic).

Figure 4. Mean diurnal variation of the equivalent slab-thickness τ over Ottawa in 1962, calculated from the mean diurnal variation of N_T and N_{max} (X) and from individual observation of N_T and N_{max} (O).

Figure 5. Comparison of mean diurnal variation of τ over Washington, D. C. and Ottawa in 1962.

Figure 6. Solar cycle variation of N_T of mid-latitude ionosphere and the mean sunspot number, $\overline{R}$.

Figure 7. Solar cycle variation of the equivalent slab-thickness of the mid-latitude ionosphere and the mean sunspot number, $\overline{R}$.

I. INTRODUCTION

The radio transmissions from artificial earth satellites have been very useful in the exploration of the ionosphere, particularly for the measurements of the total electron content, N_T, up to the height of the satellite and for studying ionospheric irregularities. The characteristics of the satellite radio signals such as amplitude, frequency, phase and direction of arrival, may all undergo significant changes during their passage through the ionosphere, provided the frequency of the radiation is not too large in comparison with the critical frequency of the F region of the ionosphere.

Measurements of the Faraday fading of the satellite signals have been used to calculate N_T by Garriott (1960), Little and Lawrence (1960), Blackband (1960), Yeh and Swenson (1961), Blumle (1962), Lawrence, et al (1963), Rogers (1964) and others. Measurements involving Doppler frequency shifts have been used to calculate N_T by Aitchison, et al (1959), Ross (1960), de Mendonca (1962) and Hibberd (1964). Garriott and de Mendonca (1963) showed that the most accurate method of obtaining N_T is a hybrid analysis using simultaneous Faraday and Doppler data. Recently, Titheridge (1964) determined the diurnal and seasonal variations of N_T and the scale height, H, of the F region, by measuring the vertical angle of arrival of the 20-Mc/s radio signals from Explorer 7 at Auckland over a period of 16 months in 1960-61 (refraction method). Measurements of the equivalent slab thickness, τ, defined as the ratio of N_T measured by satellite observation to the corresponding maximum electron density of the F region, N_{max}, have been discussed by Ross (1960), Ross and Anderson (1962), Roger (1964) and Hibberd (1964).

The present paper describes the results of the analysis of the differential Doppler data received near Washington, D. C. by the Johns Hopkins University on two pairs of harmon-

ically related frequencies (54-324 Mc/s and 150-400 Mc/s) transmitted from Transit 4A during 1962, a period of low solar activity. The method of calculating N_T has been described elsewhere (section D, Garriott and de Mendonca, 1963). Mean diurnal, seasonal and solar cycle variations of N_T and τ of the mid-latitude ionosphere will be described and compared with the results obtained by other workers.

II. EXPERIMENTAL DATA

Of 702 satellite recordings available from February 1962 to September 1962, only 259 were used in the present study. The remaining 443 recordings were rejected either because the satellite ephemeris was not available or they were so much disturbed that the "proximal point" of the satellite could not be determined. The intersection of the propagation ray path with a spherical shell at the height of 350 km is called the ionospheric point, and its vertical projection on the ground is the sub-ionospheric point. A few sample plots of N_T against geographic latitude of the sub-ionospheric point are shown in Fig. 1. While it is easy to obtain an almost continuous distribution of N_T over a small range of latitudes about the satellite receiving station, it is difficult to obtain the corresponding distribution of τ owing to the sparsity of ionosonde stations. Therefore, we shall restrict ourselves to the diurnal and seasonal variations of the ionosphere over two mid-latitude stations, namely, Washington, D. C. (40° geographic) and Ottawa ($45^{\circ}.4$ geographic) for which both N_T and N_{max} values were available. N_{max} values for Washington and Ottawa were taken from the published ionosonde data. All N_{max} values were interpolated to the corresponding local time of the satellite passage.

III. RESULTS OF THE ANALYSIS

A. DIURNAL AND SEASONAL VARIATIONS OF N_T

Figures 2(a) and 2(b) show the values of N_T up to the height of the satellite (usually greater than 880 km) over Washington and Ottawa respectively, obtained from the analysis of the differential Doppler data of Transit 4A satellite during the period February 1962 to September 1962. These values of N_T were scaled from the latitudinal plots of N_T for both the northbound and southbound passages of the satellite. The local times and the months of observations are shown at the bottom of the figures. The smoothed sunspot number, $\overline{R}$, decreased from 42 to 32 during the observing period. Although 13 geomagnetic disturbances were reported during this period, none of them was classified as severe. The storm indices ranged from $A = 10$ to $A = 40$, with a median of about 25. (Storms with A indices of about 50 or higher are classified as severe.) Therefore, all the available values of N_T were plotted in Figs. 2(a) and 2(b). Although there is scatter in the values of N_T on the order of ±20%, the diurnal variation of about 6 to 1 can be clearly seen both at Washington and Ottawa. Scatter of N_T is believed to occur mainly due to large day-to-day changes in the ionosphere and is not an indication of measurement error.

For the purpose of comparing N_T near the latitude of Washington (40°N) and that of Ottawa (45°N), the mean diurnal curves drawn manually through the points in Figs. 2(a) and 2(b) are shown in Fig. 3. The diurnal variations of N_T at these stations appear to be similar with a daytime peak that occurs in the afternoon and a minimum before sunrise. Noon values of N_T at Washington, however, were somewhat higher than those at Ottawa. This is not unexpected since a similar trend is found in the noon N_{max} values at these stations. It should be noted that the noon values of N_T in March-

April 1962 were slightly higher than the corresponding values in June-July 1962. This seems to be due to seasonal variation of N_T, although a small part of this seasonal variation may be attributed to the declining solar activity. During 1962, both the diurnal and seasonal variations of N_T at mid-latitudes diminished in amplitude as compared to the variations observed by Lawrence, et al (1963) for the Boulder and Stanford data obtained from the Faraday rotation of the signals from Sputnik 3 in 1958-59. They observed a seasonal variation in the noon values of N_T of about 2 to 1 from winter to summer and a diurnal variation of about 10 to 1.

B. MEAN DIURNAL AND SEASONAL VARIATION OF THE EQUIVALENT SLAB THICKNESS, τ

The equivalent slab thickness of the ionosphere,

$$\tau \equiv \frac{N_T}{N_{max}}$$

is evaluated from the satellite observations coupled with the corresponding values of N_{max} from ionosonde observations (Ross, 1960). For a Chapman-alpha electron density profile, we may deduce that $N_T = 4.13\ H\ N_{max}$, or that $\tau = 4.13\ H$ where H is the scale height of the ionizable constituent. Thus, the measurement of τ can be easily referred to the scale height (or temperature) of the ionized layer, if the electron density profile is reasonably close to a Chapman model. At night, this has been shown to be expected (Duncan 1956, Dungey 1956) and, for the daytime, Bowhill (1962) and Nisbet (1963) have obtained equilibrium solutions which have the same electron content as the Chapman layer, to within 10%. In the absence of thermal equilibrium, the implication of the slab thickness is not so clear, but it should represent at least approximately the mean electron-ion temperature of the plasma.

Figure 4 shows the mean diurnal variation of τ over Ottawa for the period February to September 1962 calculated in two different ways. The curve represented by (X) has been determined from the smoothed values of N_T and N_{max} at one-hour intervals from 0 to 23 hours local mean time. The second curve of τ shown by (O) has been determined by grouping the individually calculated values in similar one-hour intervals. There appears to be good qualitative agreement between the two diurnal curves of τ. It is clear that τ exhibits a significant diurnal variation at least of the order of 30%, with a peak near sunrise period. The actual diurnal variation may not be quite as large as seen in Fig. 4, since this mean diurnal curve has been developed from the data extending over a period of eight months. The occurrence of a peak in τ near sunrise has been reported by many investigators (Evans and Taylor 1961, Lawrence, et al 1963, Titheridge 1964). This has been explained by the fact that sunrise occurs earlier at greater heights so that the ionization above the peak of F layer will have considerably increased by the time the electron density at the peak begins to increase (Titheridge 1964). Also, measurements of electron temperature T_e, made by using incoherent back-scatter technique (Bowles, et al 1962) and by the Aerial satellite (Willmore, et al 1962) show evidence of a significant departure from thermal equilibrium between the electrons and ions near sunrise. This would increase the mean temperature of the electron-ion gas resulting in greater slab thickness at sunrise.

Assuming a Chapman profile for the daytime F region and atomic oxygen mass = 16 AMU, the noon values of τ at Ottawa in 1962 yield a scale height of about 87 km which corresponds to a temperature of about 1500°K. This is in excess of the neutral gas temperature T_g, which is about 1000°K as calculated by Nicolet (1963) from satellite drag analyses. This temperature difference may be attributed to the absence of the

thermal equilibrium between charged and neutral particles. The change in τ from day to the early part of the night corresponds to a temperature change of about 470°K. It is found that in 1962, the inferred mean electron-ion temperature in the early part of the night is greater than the corresponding neutral gas temperature by about 150°K. Thus, there is a definite tendency towards thermal equilibrium between the charged and neutral particles in the nighttime ionosphere.

Seasonal variation of the noon values of τ for mid-latitude ionosphere have been measured by different workers. Their results, converted to τ where necessary, are summarized in Table 1.

Table 1. Seasonal Variation of τ at Noon

Authors	Year	Place	Geomag. Lat.	Geomag. Long.	Ratio of τ in summer and winter (τ_S/τ_W)
Lawrence, et al	1958-59	Stanford and Boulder	43.7°N 48.9°N	298.4° 316.4°	1.30
Ross and Anderson	1959	University Park Pa.	52.2°N	349.1°	1.51
Roger	1959	Jodrell Bank	56.3°N	82.5°	1.49
Hibberd	1960-61	University Park Pa.	52.2°N	349.1°	1.39
Munro	1959	Baxland	42.4°S	226.5°	1.16
Titheridge	1960-61	Auckland	41.4°S	252.7°	1.20

An examination of Table 1 indicates that the seasonal variation of τ at noon in the northern hemisphere varies between 30 to 50% with a mean of about 40%, while in the southern hemisphere it is only about 20%. One possible reason for such wide variations in the noon values of τ may be the latitudinal differences in N_{max} at different stations, particularly in view of the fact that the mean electron-ion temperature depends critically on the ratio Q/N_e^2, where Q is the heat input to the electrons due to solar ionizing radiation and N_e is the electron density (Hanson, 1963).

C. EQUIVALENT SLAB THICKNESS (τ) OF THE IONOSPHERE OVER WASHINGTON AND OTTAWA

The mean diurnal curves of τ for Washington (40°N) and Ottawa (45°N) are shown in Fig. 5 for comparison. It is observed that τ at Ottawa is systematically higher than τ at Washington for much of the time except around midnight hours. At midday, the difference in τ at these stations is about 30 km. This would imply that the mean temperature of the electron-ion gas in the ionosphere over Ottawa must have been about 125°K greater than that over Washington. This conclusion seems to be consistent with the electron temperatures observed with Aerial satellite which showed that T_e increased with increasing latitude. Similar latitudinal trend in $[(T_e + T_i)/2]$ at 500 km was noticed in the analysis of the Alouette data in the fall of 1962 (Bauer and Blumle 1964).

D. SOLAR CYCLE VARIATION OF THE MIDDAY TOTAL ELECTRON CONTENT (N_T) AT MID-LATITUDES

It is a well-known fact that the critical frequency, f_oF2, of the F_2 layer varies markedly with solar cycle, being greatest at sunspot maximum. The worldwide results

have been summarized by the expression $(foF_2)^2 \propto (1 + 0.02\ \overline{R})$, where $\overline{R}$, is the mean Zurich sunspot number (Ratcliffe and Weekes 1960). It is of interest to determine a corresponding relationship between N_T and $\overline{R}$. In Fig. 6 are plotted the mean midday values of N_T at mid-latitudes against $\overline{R}$ in different months measured by various workers during the period of declining solar activity. It is evident that N_T increases linearly with $\overline{R}$, when the data are grouped by seasons, and we may express this empirical relationship as

$$N_T = a[1 + \frac{b}{a}(\overline{R} - 40)] \times 10^{17} \text{ electrons/m}^2$$

for $\overline{R} \geq 40$. The parameters a and b are constants which are different for different seasons. The variation of a, b and the ratio $\frac{b}{a}$ are shown in Table 2. The ratio $\frac{b}{a}$ represents the 'sensitivity' of N_T for changes in $\overline{R}$.

Table 2. Seasonal Variation of a, b and $\frac{b}{a}$ for $\overline{R} \geq 40$ at Mid-latitudes

Season	$a \times 10^{-17}$	$b \times 10^{-17}$	b/a
Summer	1.5	0.017	0.011
Winter	1.6	0.036	0.022
Equinox	2.0	0.05	0.025

Examination of Table 2 shows that the ratio $\frac{b}{a}$ seems to be comparable in magnitude in winter and equinox but appreciably smaller in summer. Thus, it appears that, in winter and equinox, N_T responds much the same way to the changes in

solar activity, even though the absolute values of N_T might differ in these seasons. However, it is clear that in summer, N_T increases with solar activity less rapidly than either in equinox or winter. This explains the enhanced seasonal variation of midday N_T during a period of high solar activity. Taylor (1963) and more recently Hibberd (1964) combined their mean midday values of N_T for summer and winter seasons with those of others and showed that, in winter, N_T increased linearly with 10.7 cm solar radio flux more rapidly than in summer, which is in accord with the present results.

E. SOLAR CYCLE VARIATION OF THE MID-DAY SLAB THICKNESS τ AT MID-LATITUDES

It is generally accepted that solar extreme ultraviolet radiation is an important source responsible for heating of the F region (Hunt and van Zandt 1961). Satellite drag measurements show that the thermopause temperature and hence the neutral particle densities at F region heights vary linearly with the solar activity (Nicolet 1963). In Fig. 7 are plotted the average mid-day values of τ for each season against the mean sunspot number $\overline{R}$. The empirical linear relationship between τ and $\overline{R}$ may be written as

$$\tau\ (\mathrm{km}) = 270(1 + 0.005\ \overline{R}) \quad \text{for summer,}$$
$$\tau\ (\mathrm{km}) = 240(1 + 0.005\ \overline{R}) \quad \text{for equinox,}$$
$$\text{and} \quad \tau\ (\mathrm{km}) = 210(1 + 0.005\ \overline{R}) \quad \text{for winter.}$$

Clearly, τ increases progressively from winter to summer. The seasonal variation of τ has been observed to be about 30% during the period of declining solar activity from 1958 to 1962. Additional scales for scale height H and mean electron-ion temperature $[(T_e + T_i)/2)]$, assuming mean ionic mass equal to 16 AMU, are also shown in the Fig. 7. Since

$N_T \propto N_{max} \times T$, 75% of the solar cycle variation of N_T, in equinox and winter, can be attributed to N_{max} variation and 25% to the temperature variation, whereas, in summer, N_{max} and temperature seem to make approximately equal contributions to N_T variations.

Ross and Anderson (1962) and Hibberd (1964) reported positive correlation between daytime τ and the solar activity as measured by either decimetric solar radio flux or the mean sunspot number. For southern winter, Titheridge (1964) determined the variation of H with the mean sunspot number given by

$$H = 54(1 + .0023\overline{R}) \text{ km},$$

which is approximately half as large as the corresponding variation in the northern hemisphere.

The mean electron-ion temperature inferred from the measurements of τ seems to be higher than the corresponding thermopause temperature calculated by Nicolet (1963) in all seasons. The mean electron-ion temperature $(T_e + T_i)/2$ at mid-day inferred from Sputnik 3 data and Transit 4A data, assuming a Chapman profile for the F region, are shown in Table 3, along with the neutral gas temperature (T_g) determined by Nicolet. Assuming $T_i \simeq T_g$, the ratio of T_e/T_g has been calculated for different seasons. It is seen that T_e/T_g is of the order of 1.8 in summer but tends to be progressively lower in equinox and winter. This seasonal behavior of the ratio T_e/T_g reflects similar variations in the ratio of Q/N_e^2 where Q is the heat input to the electrons and N_e is the electron density.

Table 3. Seasonal Variation of T_e and T_g at Mid-day

Year	Season	$\bar{R}$	$T_g \simeq T_i$	$(T_e + T_i)/2$	T_e	T_e/T_g
1958-59	Winter	180	1670	1720	1770	1.06
	Equinox	170	1580	1800	2020	1.28
	Summer	155	1500	2100	2700	1.8
1962	Winter	50	1000	1125	1250	1.25
	Equinox	40	975	1220	1465	1.5
	Summer	35	950	1337	1724	1.82

F. SCALE HEIGHT AND MAGNETIC ACTIVITY

As mentioned earlier, no severe geomagnetic disturbances occurred during the observing period in 1962 for which the data were available. However, Hibberd (1964) showed that, at least during some intense disturbances, the scale height increased substantially, in agreement with the results of Lawrence, et al (1963) but not with Titheridge (1964) who observed that the scale height did not vary by more than a few per cent with magnetic activity. In order to further investigate this question, we re-examined the Sputnik 3 data of Lawrence, et al (1963) for possible storm effects. A separate 'quiet' day curve of the scale height for each season was determined from the mean diurnal variation curve obtained by these authors, after correcting it for seasonal and solar cycle variation. An assumption was made that the form of the diurnal variation was independent of the season. The scale height values for $K_p \geq 4$ were regarded as 'disturbed' and these were found to be higher as well as lower than the corresponding 'quiet' day values. The effect of K_p on H is summarized in Table 4.

Table 4. Effect of K_p on H for $K_p \geq 4$ in 1959

Season	Number of Cases Showing	
	Increase in H	Decrease in H
Summer	9	17
Equinox	15	6
Winter	6	5

It is suggested by Table 4 that increases in H with magnetic activity are more common in equinox while the opposite seems to be true in summer. In winter, there is no significant tendency for H to increase with magnetic activity. Thus, at a mid-latitude station, the correlation between the scale height or mean electron-ion temperature appears to be rather ambiguous in contrast with the definite positive correlation between the neutral gas temperature and the magnetic activity (Jacchia, 1964). The reason for this apparent discrepancy may be related to the nature of different heating mechanisms for the neutral and electron-ion gas. The heating of the neutral atmosphere may be accomplished through processes such as hydromagnetic wave absorption or joule losses which do not directly contribute to the plasma temperature. However, the solar EUV radiation is generally assumed to be the main source of heat in the quiet mid-latitude daytime ionosphere. Ionospheric storms are considered to be either 'positive' or 'negative' depending upon whether N_{max} increases or decreases during the disturbance (Maeda and Sato, 1959). For a given value of heat input Q, which may be relatively constant in a storm, these variations of N_{max} may alter the ratio Q/N_e^2, which determines the temperature difference $(T_e - T_i)$, in such a way as to cause an increase or decrease in the mean electron-ion temperature and therefore the scale height.

IV. CONCLUSION

The total electron content, N_T, and the equivalent slab thickness, τ, of the mid-latitude ionosphere has been determined from the differential Doppler data of Transit 4A for the period February to September 1962. Significant diurnal and seasonal variations in N_T and τ were observed. It was found that the amplitudes of these variations were diminished considerably as compared to the earlier observations made with Sputnik 3 near the peak of the sunspot cycle. The mean diurnal curve of τ showed a peak near sunrise. The change in τ from day to night was of the order of 30% which implied a fall in temperature of the electron-ion gas of about 470°K. The seasonal variation of mid-day values of τ from summer to winter in the northern hemisphere ranged from about 30 to 50% with a mean of about 40%. This is about twice the seasonal variation of τ observed in the southern hemisphere. The effect of solar activity on the daytime equivalent slab thickness, τ could be summarized by the expression of the form $\tau \propto (1 + .005\overline{R})$ where $\overline{R}$ is the mean sunspot number. The daytime τ over Ottawa was about 30 km greater than that over Washington which implied that the mean electron-ion temperature in the F region over Ottawa was greater by about 125°K than that over Washington.

For $\overline{R} \geq 40$, it was found that the solar cycle dependence of noon values of N_T could be expressed as

$$N_T = [a + b(\overline{R} - 40)] \times 10^{17} \text{ elec/m}^2$$

where a and b are constants which are different for different seasons.

The mean electron-ion temperature in the daytime ionosphere was found to be generally in excess of the corresponding neutral gas temperature determined from the satellite

drag measurements. This is interpreted as an indication of the absence of the thermal equilibrium between charged and neutral particles. This inference is based, however, on an assumed profile shape for the electron distribution. Assuming $T_i \simeq T_g$, the daytime ratio of T_e/T_g was estimated to be about 1.8 in summer and about 1.1 to 1.2 in winter. Re-examination of Sputnik 3 data for 1958-59 showed that the relationship between the scale height or the mean electron-ion temperature and magnetic activity appears to be rather ambiguous in contrast with the definite positive correlation between the neutral gas temperature and magnetic activity.

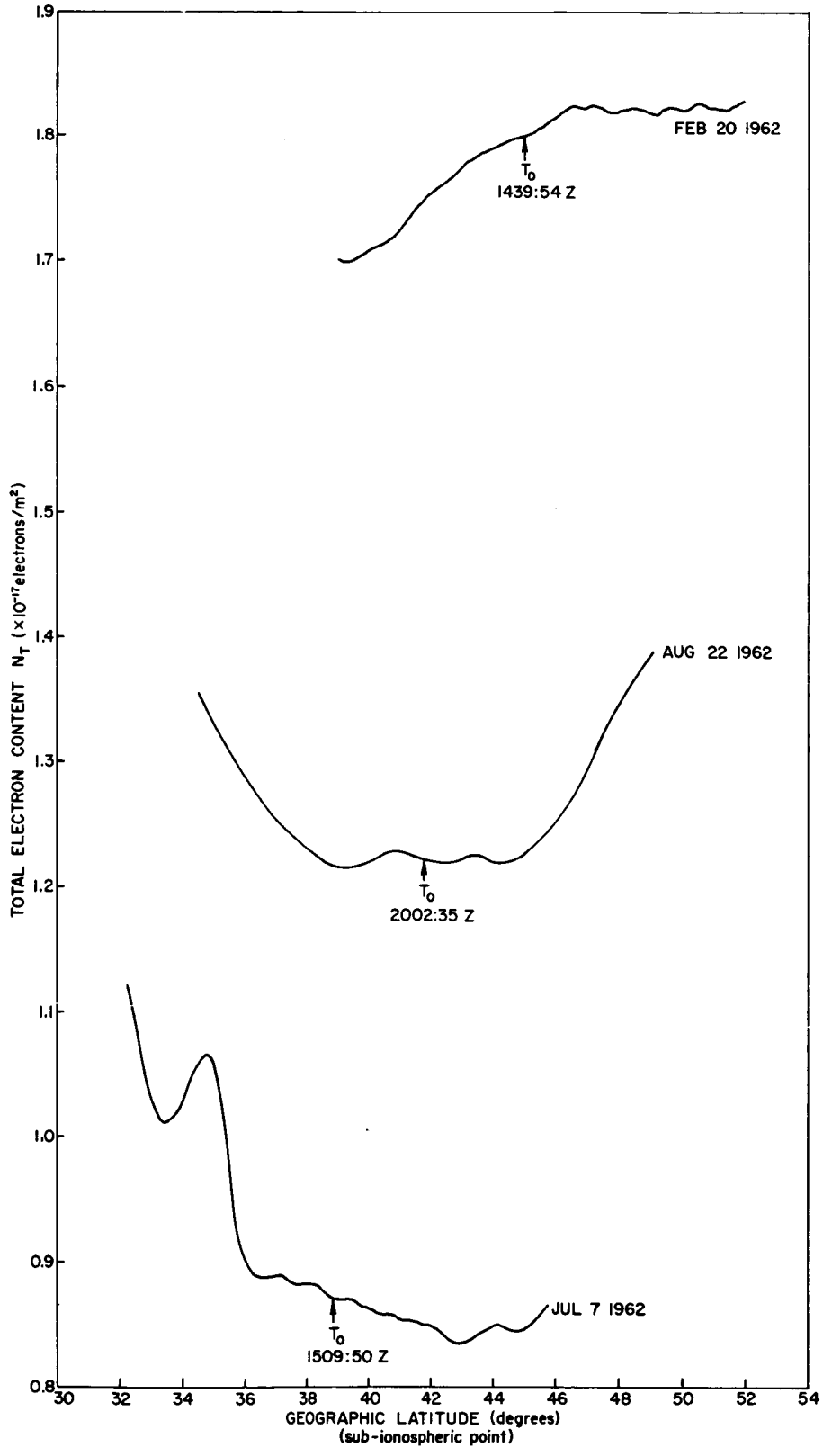

FIG. 1. SOME SAMPLE PLOTS OF N_T AGAINST GEOGRAPHIC LATITUDE OF THE SUB-IONOSPHERIC POINT OF TRANSIT 4A SATELLITE IN 1962 (T_0 REPRESENTS THE PROXIMAL POINT OF SATELLITE PASSAGE)

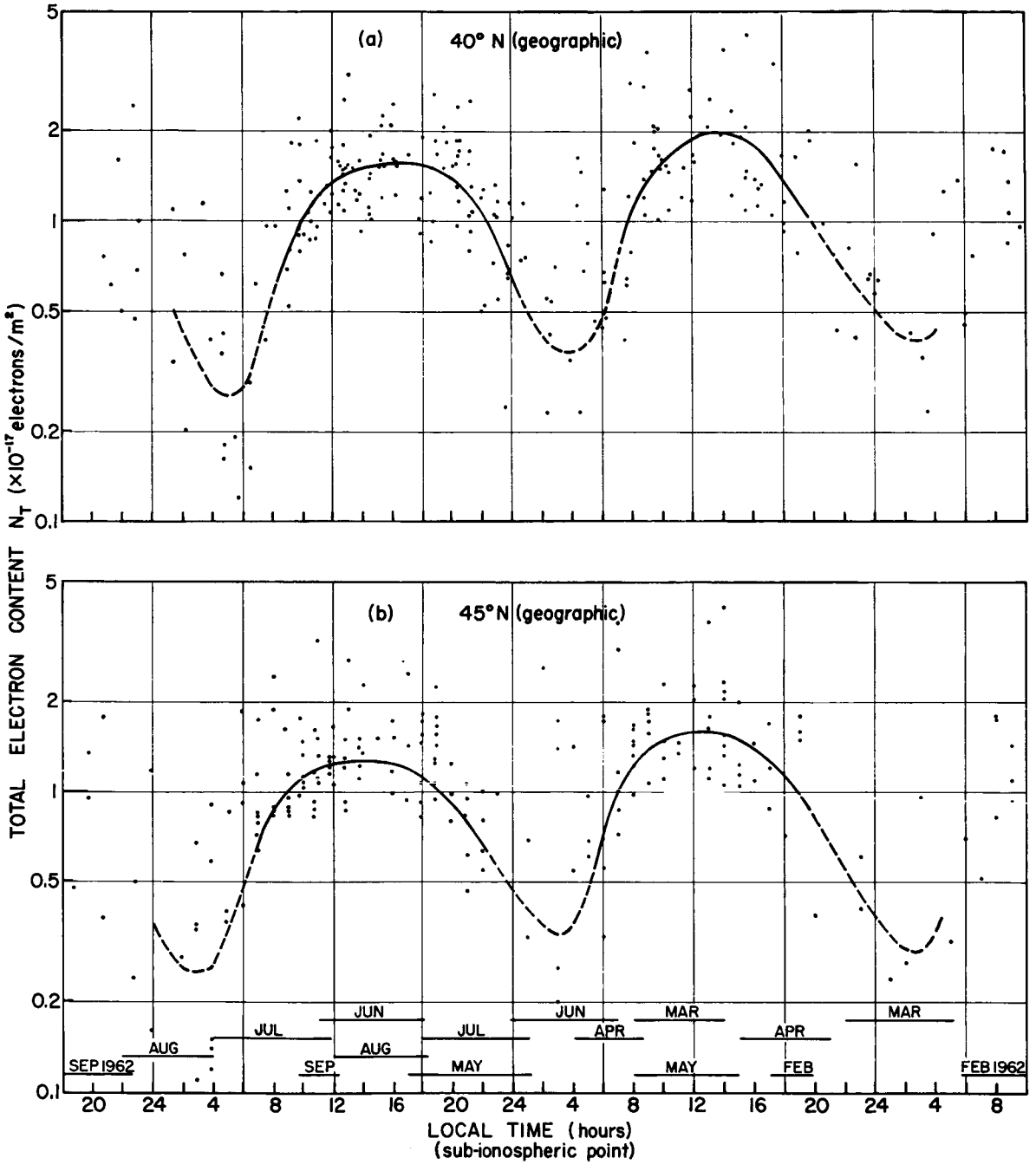

FIG. 2. THE TOTAL ELECTRON CONTENT N_T OF THE IONOSPHERE DEDUCED FROM TRANSIT 4A DIFFERENTIAL DOPPLER MEASUREMENTS AT (a) 40°N AND (b) 45°N GEOGRAPHIC LATITUDES.

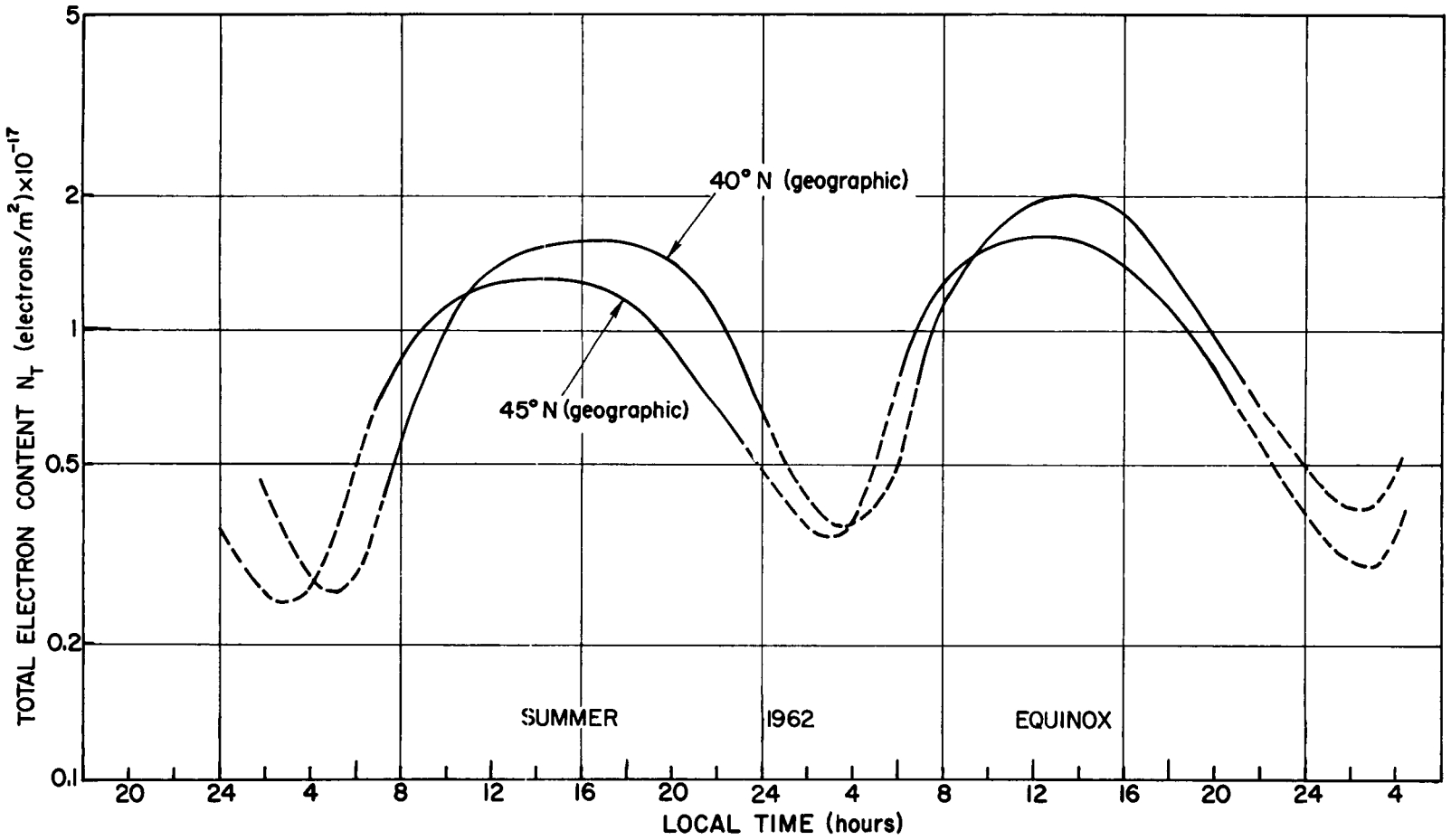

FIG. 3. MEAN DIURNAL VARIATION OF N_T AT 40°N and 45°N (GEOGRAPHIC).

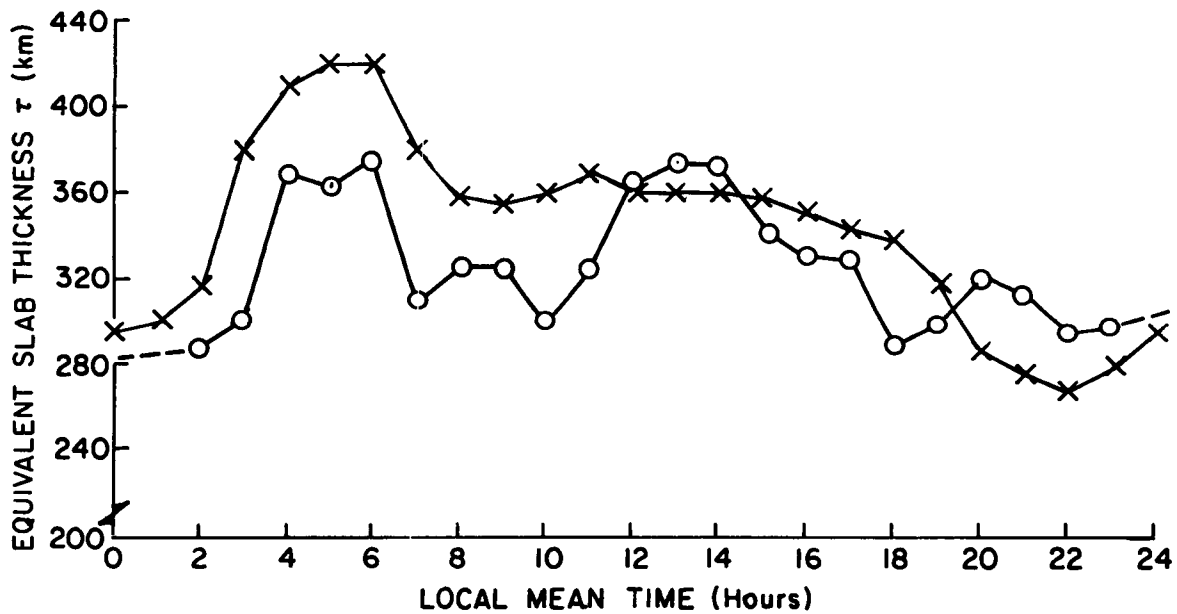

FIG. 4. MEAN DIURNAL VARIATION OF THE EQUIVALENT SLAB-THICKNESS τ OVER OTTAWA IN 1962, CALCULATED FROM THE MEAN DIURNAL VARIATION OF N_T AND N_{max} (X) AND FROM INDIVIDUAL OBSERVATION OF N_T AND N_{max} (O).

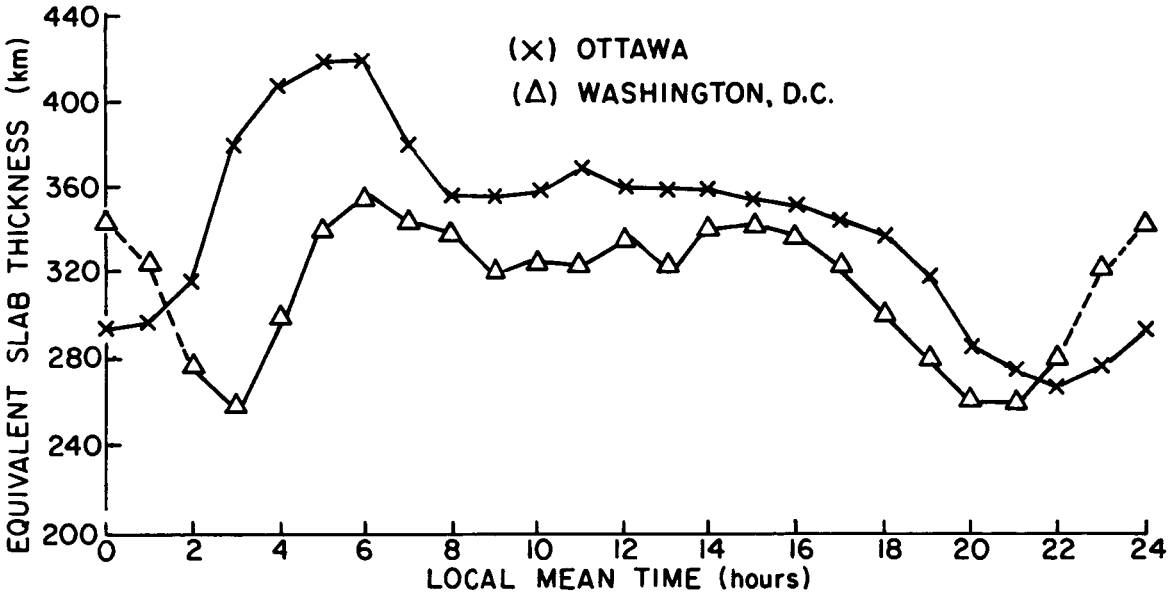

FIG. 5. COMPARISON OF MEAN DIURNAL VARIATION OF τ OVER WASHINGTON, D. C. AND OTTAWA IN 1962

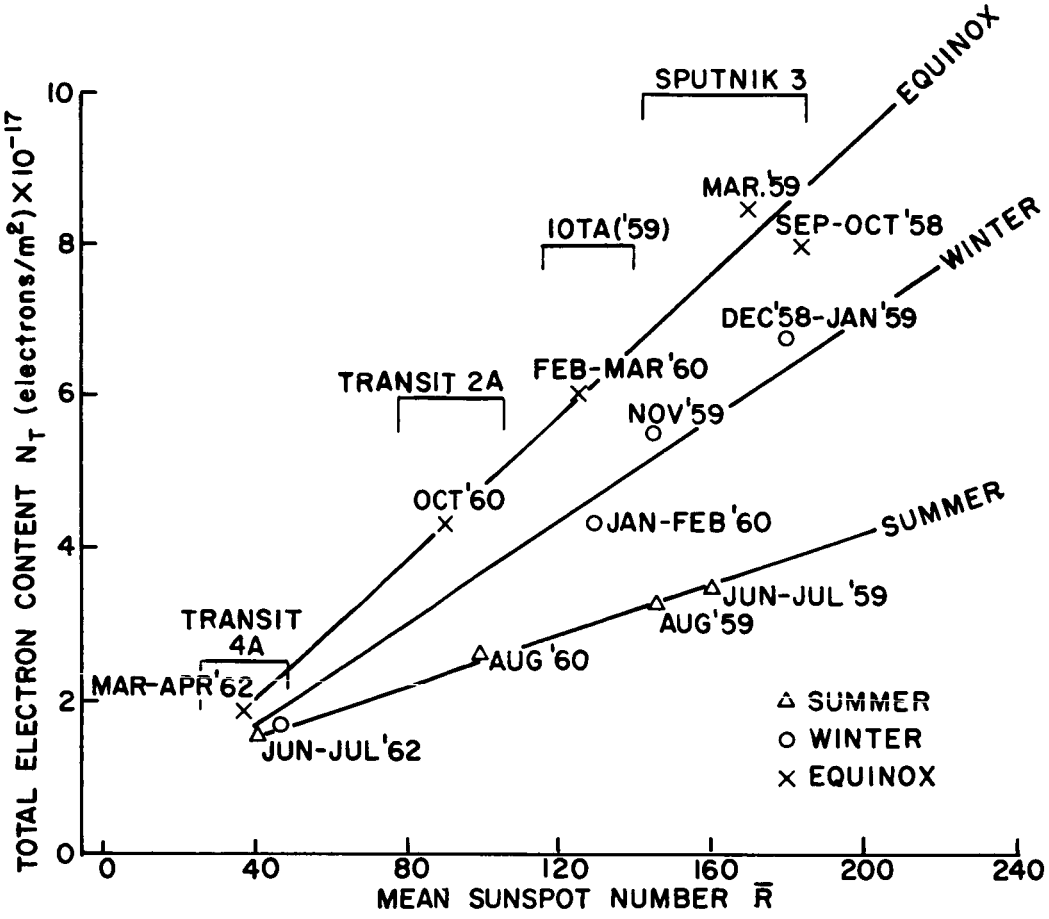

FIG. 6. SOLAR CYCLE VARIATION OF N_T OF MID-LATITUDE IONOSPHERE AND THE MEAN SUNSPOT NUMBER, $\bar{R}$.

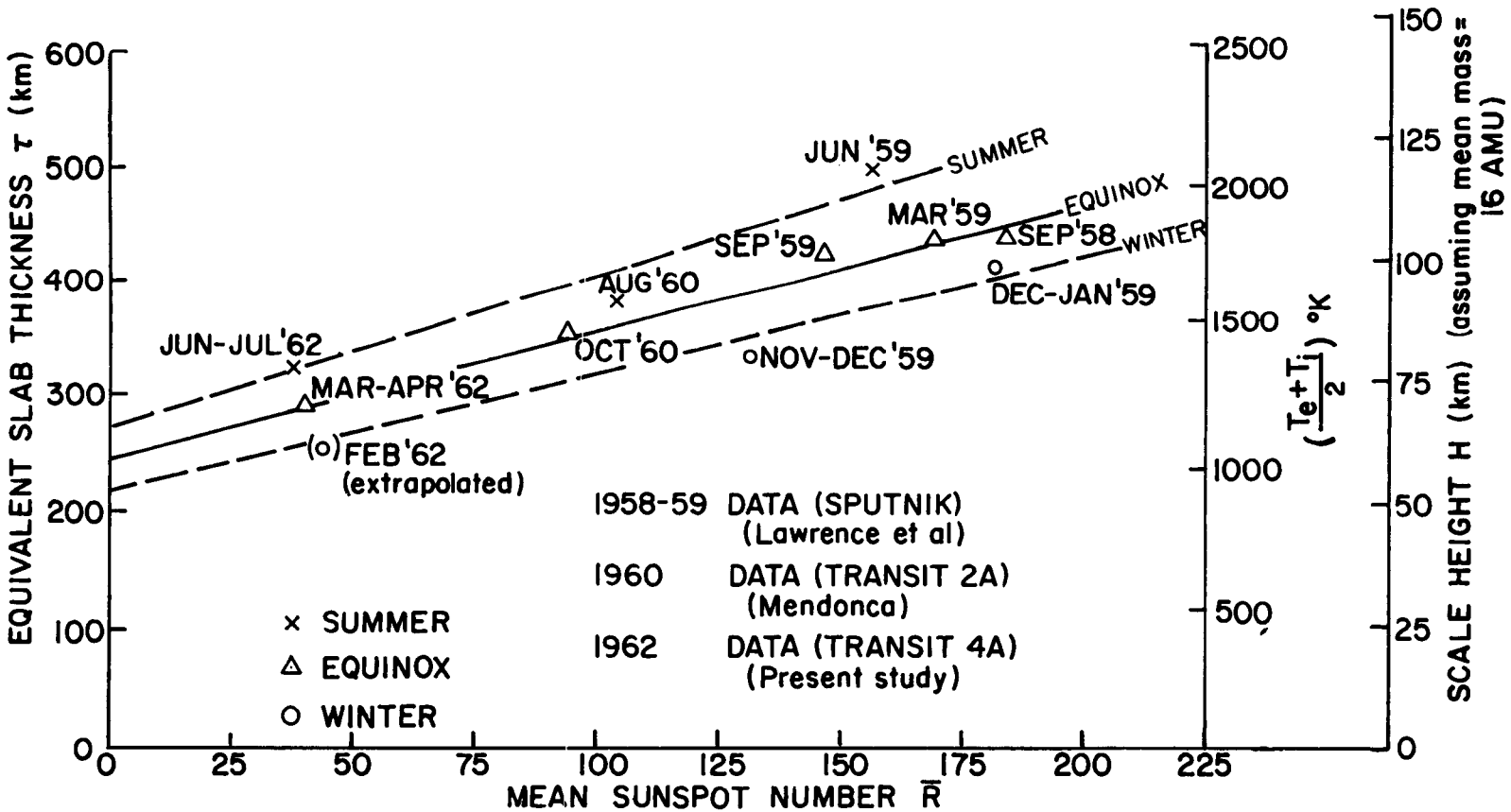

FIG. 7. SOLAR CYCLE VARIATION OF THE EQUIVALENT SLAB-THICKNESS OF THE MID-LATITUDE IONOSPHERE AND THE MEAN SUNSPOT NUMBER, $\bar{R}$.

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